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INTEGRATION OF ACPD CRACK MONITORING INTO THE DREA INSTRUMENTED IMPACT TEST SYSTEM

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FACTS ENGINEERING INC.

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ABSTRACT

A system for generating dynamic J-resistance data has been developed by integrating alternating current potential difference crack monitoring hardware into the DREA Instrumented Impact Test System. Fracture specimens were fabricated from HY80 and precracked to a/W ratios ranging from .475 to .575. Specimens were tested at ambient temperature (20°C) using an impact test system. The data provided in the dynamic J-resistance curves indicates that specimens which remain isolated from the drop tower during the impact event produce crack extensions which are in good agreement with the visually measured crack extension taken from the fracture surface.

RÉSUMÉ

Un système permettant de générer des données de résistance J dynamique a été élaboré en intégrant le matériel de contrôle des fissures par différence de potentiel en courant alternatif dans le système d'essai de choc instrumenté du CRDA. Les échantillons de rupture ont été fabriqués en HY80 et préfissurés à des rapports a/W variant entre 0,475 et 0,575. Les échantillons ont été mis à l'essai à la température ambiante (20 °C) à l'aide d'un système d'essai de choc. Les données fournies par les courbes de résistance J dynamique indiquent que les échantillons qui demeurent isolées de la tour de chute lors de l'impact produisent des allongements de fissures très semblables aux allongements de fissure mesurés visuellement sur la surface de rupture.

TABLE OF CONTENTS

	Page
Abstract	
1.0 Introduction	1
2.0 Technical Background	1
2.1 General	1
2.2 Load and Displacement Signal Measurement	1
2.3 Measurement of Crack Extension	2
3.0 System Description	4
3.1 General Description	4
3.2 System Hardware Configuration	4
3.3 System Software Configuration	5
3.4 Calibration Procedure	6
3.5 Crack Growth Calibration	7
4.0 System Operation	8
4.1 Data Input	9
4.2 Data Capture and Post Processing	10
4.3 Saving and Printing Data	10
5.0 Experimental Verification of Instrumentation	12
5.1 Specimen Preparation	12
5.2 Experimental Results	12
6.0 Conclusions	15
7.0 References	16
Appendix A - File Structures	17
A.1 Variable File	17
A.2 Load/Time File	18
A.3 Load/Displacement File	19
Appendix B - Calibration Data	20
B.1 Range 5VDC-X10	20
B.2 Range 1VDC-X100	20
B.3 Range 2.7VDC-X100	20
B.4 Range 5VDC-X100	20

1.0 INTRODUCTION

Recently, DREA/DL independently commissioned the development of two hardware/software systems for utilization with instrumented impact testing. The first system, developed by FACTS Engineering Inc. (FACTS), was an integrated system for capturing and processing dynamic force/time signals into force/displacement data [1]. The primary use of this system has been to develop temperature transition curves for various steels and weldments. The second system, developed by Techno Scientific Inc. (TSI), was an alternating current potential difference system monitoring crack growth in systems experiencing dynamic loading [2].

The combination of these two systems will potentially allow researchers to generate dynamic J-resistance curves for various metallic materials. The focus of this study is to integrate these two systems and to evaluate the accuracy of the system by generating J-resistance curves for HY80 specimens at ambient temperatures.

2.0 TECHNICAL BACKGROUND

2.1 General

In order to qualify structural steel and weldments for use in the fabrication of marine structures, they must pass test procedures which impose conditions that exceed expected operational service requirements. Fracture mechanics is the study of the interaction between defects, applied stress, geometry, and materials properties. Defects can be formed during the material processing stage (rolling laminations), during fabrication of structure (weld defects), or formed as a result of the in service stresses and strains applied to the structure (fatigue cracking). Cracks will continue to grow by subcritical mechanisms until they reach a critical length at which point they will initiate and propagate. These cracks can propagate under limit state conditions either by ductile tearing where the mechanism is dominated by microvoid coalescence or by brittle propagation which is dominated by transgranular cleavage.

The information required for an instrumented impact fracture analysis is a) the signal produced by a calibrated load cell (tup) with respect to time, b) the load line displacement of the specimen with respect to time, and c) crack extension with respect to time.

2.2 Load and Displacement Signal Measurement

Load is normally measured using piezoelectric cells or small semiconductor strain gauges arranged in a full bridge configuration. MacGillivary et al [3] have published that 300 kHz at -3 dB is an acceptable signal amplifier/conditioner frequency response time for a bend bar impacted at 5 m/s.

Load line displacement has been successfully measured using both mechanical [4] and optical devices [5]. Because of the unpredictable nature of dynamic testing, displacement gauges are destroyed periodically by the specimen being tested. An alternative method of generating load

time displacement is to convert force/time into force/displacement using conservation of energy principles. To convert the force/time data to force/displacement, the velocity at each moment must be known. If system friction is assumed to be negligible, the initial impact velocity (V_0) may be calculated from the initial height (h_0) of the hammer assembly as:

$$V_o = \sqrt{2gh_o} \tag{1}$$

where g is the acceleration due to gravity. As the specimen is contacted, there is a loss of energy and an associated loss of velocity, as follows:

$$m\int VdV + mg\int dh - \int P_o V_o dt = 0 \tag{2}$$

where m is the mass of the instrumented hammer and P is the force recorded at the load line during the test. The energy absorbed by the specimen (represented by the third term) is approximated by the area from time i to i+1 under the force time curve multiplied by the average velocity from time i to i+1. The second term calculates the potential energy converted to kinetic energy due to vertical displacement of the striker assembly. In this manner, the velocity can be calculated for all times and the time can be converted to displacement by continually dividing time increments by the average calculated velocity during these periods.

2.3 Measurement of Crack Extension

Several different techniques are available for the measurement of crack extension in fatigue precracked specimens during laboratory fracture tests (e.g. J, CTOD, R-curve). The simplest method uses visual measurements taken from the specimen fracture surface. For the development of a crack growth resistance curve, this multi-specimen approach is very demanding of time and material, and results in considerable data scatter, particularly when testing such inhomogeneous material as weld fusion zones. For quasi-static testing, single specimen techniques have been developed involving semi-continuous monitoring of crack length using such methods as unloading compliance [6], electrical resistance [7] and potential drop measurements [8]. Some of these techniques have been incorporated into standardized fracture test methods. Unfortunately, compliance measurements and direct current potential difference techniques (DCPD) are impractical or ineffectual at dynamic loading rates.

Recently, the "key curve" or "normalization" technique was proposed for the indirect determination of crack extension from specimen load-displacement records [9]. The basis of the normalization technique is the assumption that the load for a test can be described by two multiplicative functions in the form;

$$P = G(a/W)\ H(pl/W) \tag{3}$$

where G(a/W) is determined from the J calibration for the specimen geometry. If H(pl/W) can be accurately modelled, then crack extension information can be generated directly from the experimental load-displacement data using an iterative numerical algorithm. Landes and Herrera conducted several investigations [10,11] where various functional forms describing the relationship between load and normalized displacement for various steels were evaluated. One form, termed the "LMN" function [10], has been shown to accurately describe normalized load versus normalized displacement for a variety of differing materials. This method can be applied to both static and dynamic test methods to generate crack extension information required for the development of resistance curves.

An alternative method to generating crack extension which shows considerable promise is inputting a high frequency alternating carrier signal across the specimen while monitoring the changes in potential across the crack front as the crack advances (ACPD). One advantage of using ACPD over DCPD is that the frequency response of the signal is improved. A second advantage is that by using a discrete fourier transform (DFT) technique, the information in the carrier signal can be selectively removed from any mechanically induced noise that significantly reduces the ability to retrieve accurate crack extension information from dynamic DCPD signals.

The basis of discrete fourier transform theory lies in converting periodic time domain voltage data into an amplitude/ frequency spectrum. The coefficients (a_k) of this frequency spectrum, each of which represent the various frequencies contained in the time domain data, can be generated by:

$$a_k = \frac{1}{N} \sum_{n=0}^{N-1} x[n] \exp(-j2\pi kn/N) \qquad (4)$$

where a_k represents the kth spectral component and N is the number of sample values. Once the time domain data is converted into its frequency spectrum, the frequency of interest can be selectively retrieved from this spectrum by multiplying the real and imaginary components of the spectral coefficients by an impulse function with similar spectral frequency components. The resulting spectral frequency domain can be converted back into time data using:

$$x[n] = \sum_{k=0}^{N-1} a_k \exp(j2\pi kn/N) \qquad (5)$$

The following section describes the hardware and the software components of the system developed over the course of this study.

3.0 SYSTEM DESCRIPTION

3.1 General Description

The system has three major instrumented subsystems (Figure 1). The first subsystem is the dynamic load sensor for monitoring the resisting specimen force during the fracture process. The force sensor utilizes a commercially available semiconductor strain gauged tup where the gauges are arranged in a full bridge. The signal produced by this sensor is rooted into a 100 kHz amplifier/signal conditioner.

The second subsystem is the ACPD hardware. A 40 kHz function generator is used to input an AC current across the specimen. Current input leads are placed at the ends of the specimen at the W/2 position. Two leads are positioned on the lower face of the specimen on each side of the plane of the crack for measuring crack length potential. The potential generated across the crack front is rooted to a second high speed amplifier/signal conditioner.

The signal from the load sensor and the crack potential from the ACPD hardware are bussed into an A/D converter which digitizes the signal at a sampling rate of 50 ns. The digitizer contains buffered FIFO memory which latches 64 kilobytes of data once the system has been triggered (32 kilobytes of load data and 32 kilobytes of crack extension data). This data is retrieved and stored in permanent memory using the custom software interface for subsequent post processing into J-resistance curve information.

3.2 System Hardware Configuration

The following list describes the hardware devices required for the system:

- IBM 586 compatible microprocessor
- SVGA terminal
- Microsoft compatible mouse
- 101 enhanced keyboard
- Gage Applied Sciences Inc CSLITE (64K A/D board)
- Vishay 2300 signal conditioner/amplifier
- TSI crack monitoring interface

A schematic of the hardware interconnections is shown in Figure 1. Connect the TUP cable to the back panel connector labelled INPUT on the Vishay 2311 signal conditioner/amplifier (for pin out specifications refer to the ETI and Vishay User Manuals). The CSLITE A/D board is installed into an ISA slot on the PC 586 mother board and the back panel output BNC connector labelled TAPE on the Vishay 2311 is connected to the CSLITE back panel connector labelled CH A (use a shielded BNC connector). Connect the red leads from the TSI crack monitoring interface to the current connectors at the ends of the specimen. Connect the black potential leads from the TSI crack monitoring system to the potential connectors on the bottom face of the specimen. Connect the shielded BNC connector on the TSI crack monitoring interface to CH B on the CSLITE A/D digitizing card.

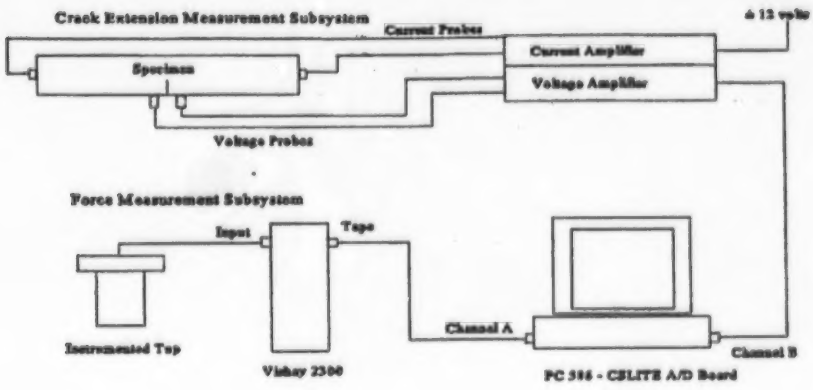

Figure 1 - Schematic representation of DREA instrumented impact test system hardware configuration.

3.3 System Software Configuration

The software package consists of a single executable " ACPD.EXE" and two dynamic link libraries "CW3215.DLL" and "GAGE3DRV.DLL" which combine to generate a custom designed virtual instrument which executes the data acquisition and J-resistance curve analysis. The system was designed for Windows 95/98, a 32 bit environment and will not execute properly in 16 bit environments such as DOS or Windows 3.1. If the custom software requires reinstallation, the following steps should be followed:

a) Insert the installation disk into drive A:

b) Enter the command A:INSTALL<CR> from the keyboard (this can be done from either DOS or Windows environments).

Once the software has been reloaded onto the system, make sure that the data file "cal.txt" contains the proper calibration factors. This file can be viewed using a commercially available text editor (not a word processor).

3.4 Calibration Procedure

The instrumented impact system requires periodic calibration verification of the force transducer to ensure the accuracy of the data. This verification is achieved through a static calibration procedure.

1. Attach the tup to the conditioner input and a voltmeter to the output of the conditioner as detailed in the System Description section.

2. Apply an axial compressive load to the instrumented tup using a calibrated servo hydraulic test system or comparable device.

3. Record the calibrated load versus the output voltage at a minimum of ten positions over the full scale range. Plot the data and visually verify the linearity of the force-voltage output.

4. Determine the calibration coefficient in units of kN/volt

5. Repeat steps 2-4 for each system amplifier range/excitation voltage combination used by the system.

6. Update the "cal.txt" file located in the system root directory with the current calibration coefficients.

This procedure was used to generate the current calibration factors representing various load ranges. The raw data used as input to the regression analysis is given in Appendix B. A summary of the information in Appendix B is given in Table 1 and shown graphically in Figure 2.

Table 1 - Current system calibration factors

Instrument ID	Calibration Factor (kN/Volt)	Full Scale Load Range (kN)	Amplifier Excitation Voltage (Volts)	Amplifier Gain
E5/G10	624.86	624.86	5.0	10
E1/G100	318.00	318.00	1.0	100
E2.7/G100	117.01	117.01	2.7	100
E5/G100	63.89	63.89	5.0	100

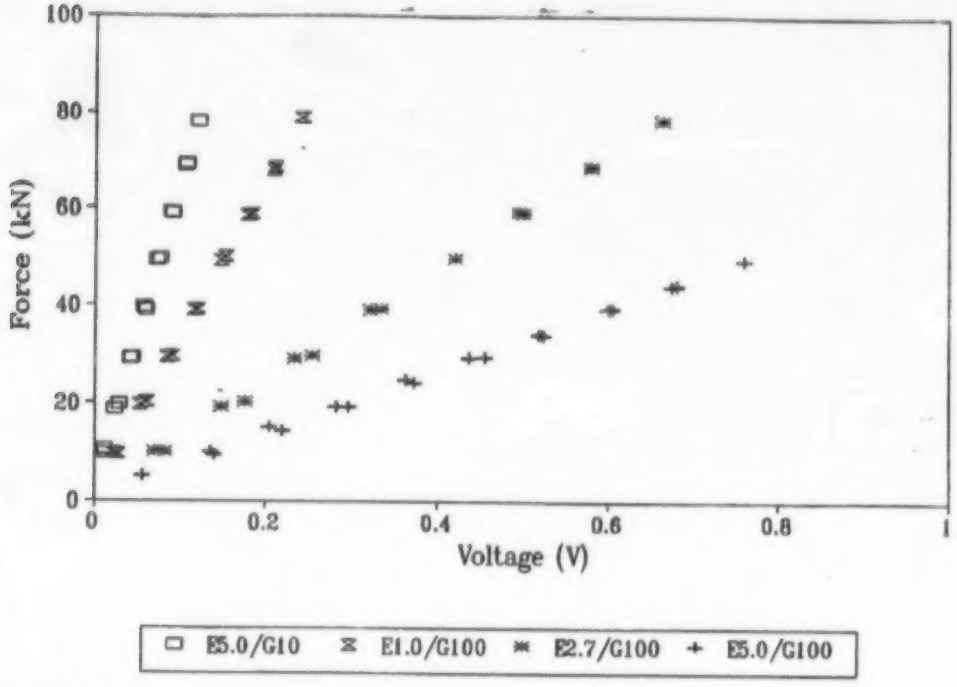

Figure 2 - Calibration curves (force versus voltage) for the four system transducer ranges.

As prescribed in ASTM E-04, transducer verification/calibration should be performed once a year. If the calibration coefficients vary more than 1% from the previous calibration coefficients, then this period should be decreased to 6 months. Also, the Vishay 2311 automatically monitors the resistances in the force transducer. If gauge resistances are mismatched between 1%-5%, the yellow HI LED will be activated. If the gauge resistances are mismatched by more than 5%, the yellow HI LED blinks, indicating a serious transducer problem. Changes in transducer resistances should result in an immediate recalibration of the system.

3.5 Crack Growth Calibration

ASTM E-1737 contains various expressions for monitoring crack lengths in various specimen geometries using DCPD devices. Since the principles of crack length measurement in both DCPD and ACPD is based on changes in resistance across the crack front, these equations should be equally applicable to ACPD measurements. The equation used in this study is an experimentally derived solution given by:

$$\frac{a}{W} = \left[0.2864\left(\frac{U}{U_0} - 0.5\right)\right]^{0.3506} \qquad (6)$$

where U is the instantaneous voltage measured by the system. Since this equation is normalized to an a/W ratio of 0.5, for specimens with a/W ratios differing from 0.5, U_0 can be calculated by:

$$U_0 = \frac{U_B}{3.4916\left(\frac{a_o}{W}\right)^{2.851} + 0.5} \qquad (7)$$

where U_B and a_0 are the voltage and crack length, respectively, at the onset of the test.

4.0 SYSTEM OPERATION

The DREA instrumented impact testing system is an R&D oriented software package designed for gathering and analysing dynamic force time data. Once the system has been configured, data base generation and maintenance is self supervising. Using this system requires no previous experience with computers. The system has a single control display which allows the operator complete access to the program functions. To initiate the program and generate the control display, choose the ACPD icon from the Windows program menu.

A bit map of the user interface associated with this program is shown in Figure 3. The display is divided into four sections. The column of windows located on the left hand side of the display are for the input of client, test apparatus, test specimen and procedure description. While these variables do not affect the acquisition of the data, several of them are used for post processing. The variables associated with these windows can be up to 100 characters long. The initial screen displays the data types associated with each of the windows.

The bottom centre/right section of the screen contains various check boxes, scroll bars and track bars which are used to set up and control the digitizer during data acquisition. The operator can set test parameters such as transducer range, digitizing rate, trigger level and the trigger delay. The system has been preprogrammed with valid CSLITE settings to minimize operator error during digitizer setup.

The upper centre/right section of the screen contains the check boxes and track bars used to activate data capture and control post processing of the data displayed immediately below these controls. The operator can define the point of initial impact and final fracture.

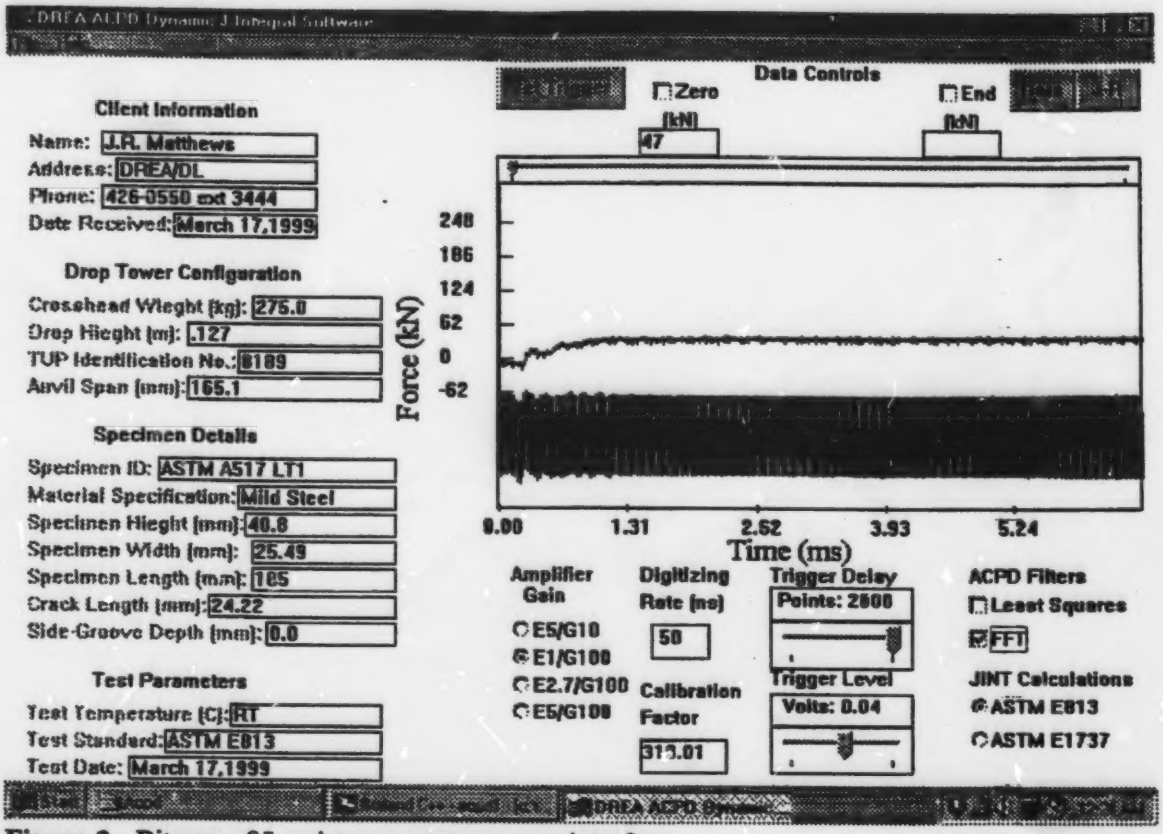

Figure 3 - Bitmap of J-resistance program user interface.

The final section of the display is the command menu located along the top of the display. The command menu allows the operator to input variables from ASCII text files as well as output captured data to either ASCII text files or to a hardcopy device such as a printer or plotter. The command menu also has an online help section to assist the user to correctly configure and calibrate the hardware as well as set up and capture data using the software interface. The following sections detail data input, data capture/post processing and data output.

4.1 Data Input

There are three methods available for inputting configuration data to the system. Upon system initialization, the user can manually enter data into the description variables and digitizer control buttons. Alternatively, if a variable data file was previously saved as "ID.var"(section 4.3), then this file can be recalled to automatically configure the system to the previously saved configuration. In a similar manner, a variable/test file "ID.tim" (this is the file saved at the successful capture of impact data) can be recalled to automatically configure the system. The basic procedure for inputting a file is the same regardless of file type and is given as:

a) Choose FILE/OPEN from the command menu.
b) Set the file type using the file type menu.
c) Click on the name of the file to be opened.
d) Click on OK box in the Open File window box.

Regardless of the manner in which the system is configured, the system should now be ready for data capture.

4.2 Data Capture and Post Processing

Once the system has been properly configured (see section 4.1), the digitizer can be activated by clicking on the "SET TRIGGER" button. The system will remain activated for 20 seconds. If the trigger level conditions are met, then the system will capture the load/time trace and display the trace on the terminal. If the trigger condition times out, a message to this effect will appear on the screen. ***Immediately upon the successful capture of an impact trace, save this file (section 4.3) to avoid the possible loss of valuable data.***

Post processing of impact data is achieved using the "ZERO", "END", and "JR" buttons combined with the graph track bar located at the top of the graph. The point of impact can be selected by clicking on the "ZERO" button. Pulling the track bar pointer in combination with the keyboard arrow keys is used to isolate the position of initial impact. Accurately defining the point of initial impact is necessary in order to define the initial velocity conditions for the numerical algorithm which converts load/time to load/displacement using conservation of energy principles. The point of final fracture can be similarly defined by clicking on the "END" button and using the track bar and keyboard arrow keys. The system has data boxes to display force values associated with the zero and end positions.

4.3 Saving and Printing Data

There are four different types of files which the operator can save to disk storage. File structures for these different types of files are given in Appendix A. The first type is a test variable file which saves the current settings of the test description and digitizer configuration variables. This file is saved using the ".var" file descriptor (adjust the file type list to the "*.var"). The second and probably the most commonly saved type of file is the load/time data file. Saving load/time data is done immediately after the successful capture of a new instrumented impact record. This file is saved using the ".tim" file descriptor (the "*.tim"file type is the default setting). If the operator requires a data file containing load/displacement couplets for the displayed data, this can be achieved by saving the file using the ".lpd" file descriptor (adjust the file type list to the "*.lpd"). If the operator requires a data file containing applied J/crack extension couplets, this can be achieved by saving the file using the ".jr" file descriptor (adjust the file type list to the "*.jr"). Both ".lpd" and ".jr" data file types can be imported into most commercially available spreadsheet and graphing packages. The basic procedure for saving a file is the same regardless of file type. This is given as:

a) Choose FILE/SAVE from the command menu.
b) Set the file type using the file type menu.
c) Input the name of the file to be saved (include the file descriptor).
d) Click on OK box in the Save File window box.

A hardcopy of the load displacement data associated with the current screen display can be obtained by choosing the FILE/PRINT option from the command menu.

5.0 EXPERIMENTAL VERIFICATION OF INSTRUMENTATION

5.1 Specimen Preparation

To provide an experimental verification of the accuracy of the ACPD system developed, 25.4 mm thick specimens of HY80 were tested at 20°C. Prior to testing, the specimens were precompressed to 0.4 of the specimen limit load and fatigue precracked at a stress intensity of approximately 38 Mpa$\sqrt{m}$. The three-point-bend specimens were impacted between 1.4 and 1.7 m/s with a 275 kg crosshead. The signals from the instrumented load transducer and ACPD voltage probes were routed through their respective signal conditioners/amplifiers. The amplified signals were bussed from the amplifier to the 8 bit digitizer where the signal was captured and stored for subsequent analysis. Subsequent to testing, the specimens were heat tinted and the initial fatigue crack and the final crack extension were measured.

5.2 Experimental Resuits

Figures 4 through 7 represent the raw data and J-resistance records for the two specimens tested. Table 1 contains the results from the visually measured crack extensions for these specimens. Comparison of the crack extension predicted by the ACPD system and the visually measured cracks indicate good agreement for specimen AUS17 indicating that equations 6 and 7 are accurate for ACPD systems. For specimen AUS18, the crack extension predicted by the software algorithm is significantly longer than the crack extension measured on the specimen fracture surface. Figure 6 shows considerable noise and two large voltage spikes in the ACPD data for specimen AUS18. Visual inspection of the upper piece of insulating laminate upon test completion revealed longitudinal splitting of the laminate. A loss of isolation between the specimen and tower could explain the excessive noise contained in this trace which inturn resulted in the poor prediction of the final crack extension for AUS 18.

Table 1 - Predicted and measured crack extensions for the tested specimens.

Specimen ID	Predicted Crack Extension (mm)	Measured Crack Extension (mm)
AUS17	0.47	0.52
AUS18	2.04	0.56

Visually, the J-resistance data for AUS17 conforms to the power law morphology expected from a tough material such as HY80. The ACPD signal oscillated slightly for approximately 1 ms after impact, resulting in inaccurate crack extension data at the beginning of the J-R curve. The scatter in the crack extension generated by the ACPD data continually reduces as the test proceeds.

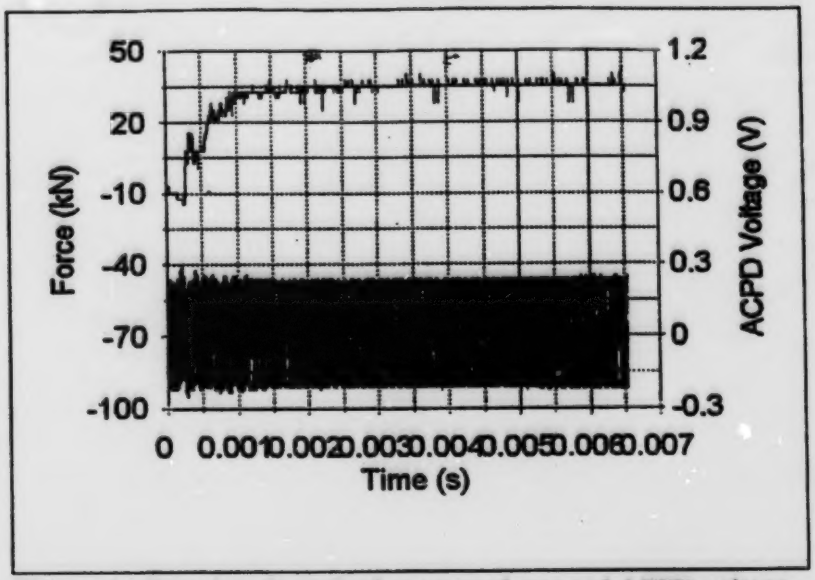

Figure 4 - Raw data from the force transducer and ACPD voltage probes (specimen AUS 17).

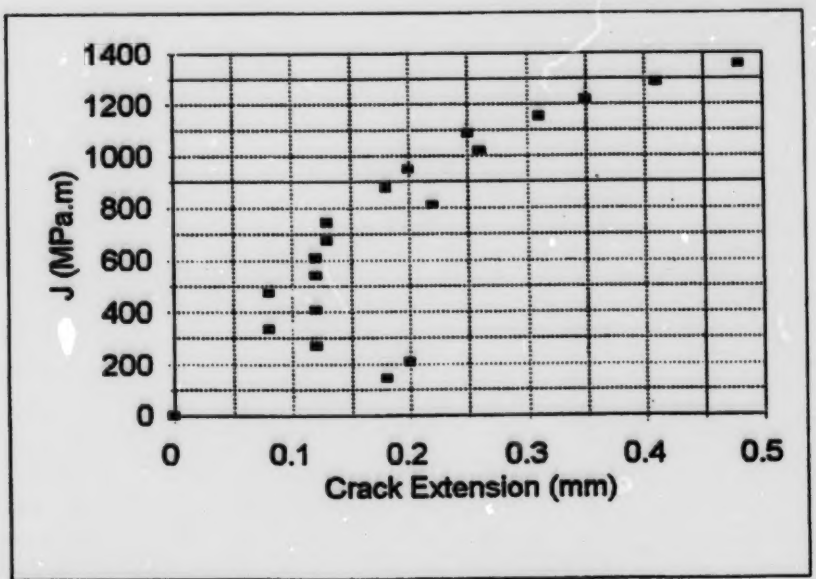

Figure 5 - J-Resistance data for specimen AUS17 (20 °C).

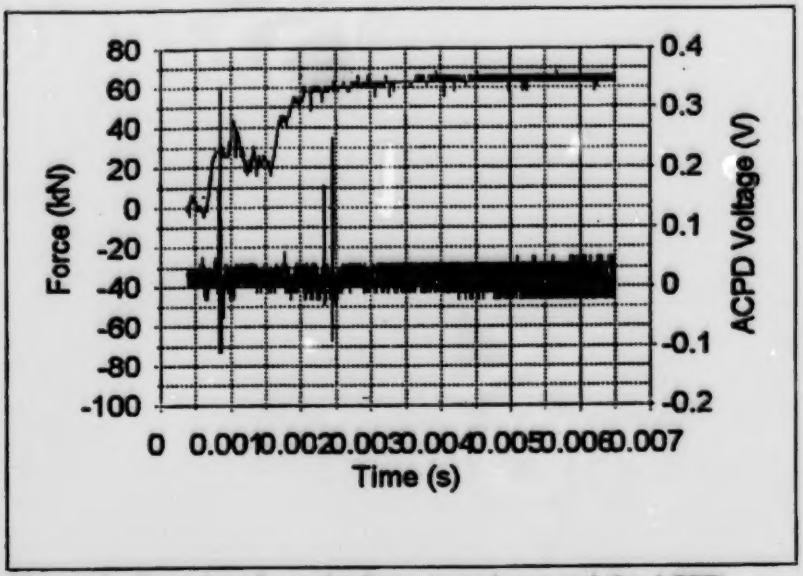

Figure 6 - Raw data from the force transducer and the ACPD voltage probes (specimen AUS18).

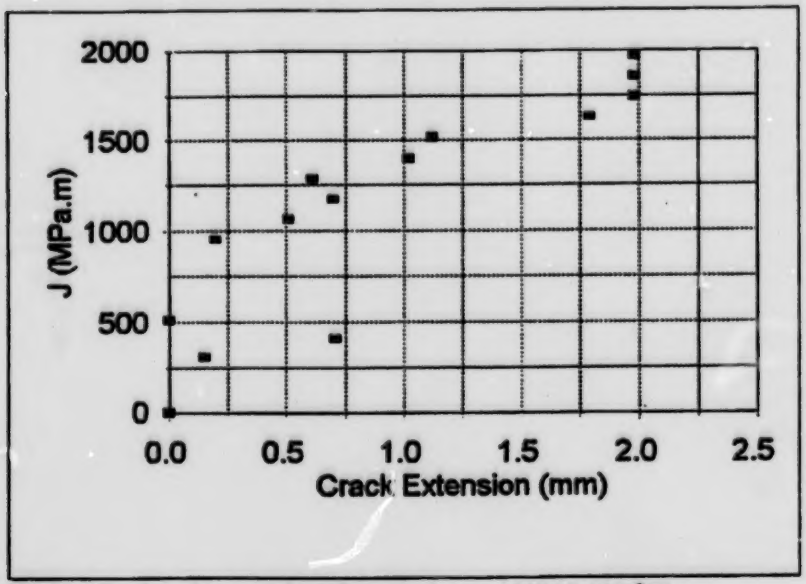

Figure 7 - J-resistance data for specimen AUS18 (20 °C).

6.0 CONCLUSIONS

A system for generating dynamic J-resistance data has been developed by integrating alternating current potential difference crack monitoring hardware into the DREA Instrumented Impact Test System. Precracked specimens of HY80 were impacted at rates between 1.4 and 1.7 m/s. The following inferences are concluded from an examination of the raw data files and the generated J-resistance curves.

1) In order for the system to provide accurate crack extensions, the specimen must remain isolated from the tower during the impact event.

2) Specimens which remain isolated from the tower produce crack extensions which are in good agreement with the visually measured crack extension taken from the fracture surface.

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Appendix A - File Structures

A.1 Variable File (*.var)

File Identification Code (variable file is 1001) <CR>
Name (text - max 100 characters) <CR>
Address (text - max 100 characters) <CR>
Phone No. (text - max 100 characters) <CR>
Test Date (text - max 100 characters) <CR>
Weight (float - kg) <CR>
Drop Height (float - m) <CR>
Tup ID (text - max 100 characters) <CR>
Anvil Span (float - mm) <CR>
Specimen ID (text - max 100 characters) <CR>
Material Spec (text - max 100 characters) <CR>
Specimen Height (float - mm) <CR>
Specimen Width (float - mm) <CR>
Specimen Length (float - mm) <CR>
Specimen Crack Length (float - mm) <CR>
Specimen Side Grooves (float - mm) <CR>
Temperature (text - max 100 characters) <CR>
Test Standard (text - max 100 characters) <CR>
Current File (text - max 100 characters) <CR>
Excitation/Gain (Integer - 1, 10, 100, 1000 - Excitation and gain set during calibration) <CR>
Calibration Factor (float - kN/volt) <CR>
Digitizing Rate (Integer - 1, 2, 5, 10, 20 - sweep time per point in microseconds) <CR>
Channel A Status (Integer - 0=OFF, 1=ON) <CR>
Channel B Status (Integer - 0=OFF, 1=ON) <CR>
Points in Trigger Delay (Integer - 0 to 2000) <CR>
Trigger Source (Integer - 0=Channel A, 1=Channel B) <CR>
Trigger Level (Integer - 0 to 255 represents -1.0V to 1.0V)<CR>
<EOF>

A.2 Load/Time File

File Identification Code (variable file is 1001) <CR>
Name (text - max 100 characters) <CR>
Address (text - max 100 characters) <CR>
Phone No. (text - max 100 characters) <CR>
Test Date (text - max 100 characters) <CR>
Weight (float - kg) <CR>
Drop Height (float - m) <CR>
Tup ID (text - max 100 characters) <CR>
Anvil Span (float - mm) <CR>
Specimen ID (text - max 100 characters) <CR>
Material Spec (text - max 100 characters) <CR>
Specimen Height (float - mm) <CR>
Specimen Width (float - mm) <CR>
Specimen Length (float - mm) <CR>
Specimen Crack Length (float - mm) <CR>
Specimen Side Grooves (float - mm) <CR>
Temperature (text - max 100 characters) <CR>
Test Standard (text - max 100 characters) <CR>
Current File (text - max 100 characters)<CR>
Excitation/Gain (Integer - 1, 10, 100, 1000 - Excitation and gain set during calibration) <CR>
Calibration Factor (float - kN/volt) <CR>
Digitizing Rate (Integer - 1, 2, 5, 10, 20 - sweep time per point in microseconds) <CR>
Channel A Status (Integer - 0=OFF, 1=ON) <CR>
Channel B Status (Integer - 0=OFF, 1=ON) <CR>
Points in Trigger Delay (Integer - 0 to 2000) <CR>
Trigger Source (Integer - 0=Channel A, 1=Channel B) <CR>
Trigger Level (Integer - 0 to 255 represents -1.0V to 1.0V) <CR>
No. of Data Points in File (Integer) <CR>
Start Data String (char - 0 to 255) ..... End Data String (char - 0 to 255) <CR>
<EOF>

A.3 Load/Displacement File

File Name (File Name: Text) <CR>
Specimen ID (Specimen ID: text) <CR>
Total Energy (Total Energy: float - Joules) <CR>
Cursor Energy (Cursor Energy: float - Joules) <CR>
Start Selected Load/Displacement Data Interval (float - mm, float - kN) <CR>

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End Selected Load/Displacement Data Interval (float - mm, float - kN) <CR>
<EOF>

A.4 J/Δa File

File Name (File Name: Text) <CR>
Specimen ID (Specimen ID: text) <CR>
Start Selected J/Δa Data Interval (float - KPa.m, float - mm) <CR>

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End Selected J/Δa Data Interval (float - KPa.m, float - mm) <CR>
<EOF>

Appendix B - Calibration Data
(TUP Calibration (DREA/DL) Serial No. 07148)

B.1 Range 5VDC-X10

Instron % FS (%)	Impact System (Volts)	Instron Force (kN)
0	-0.0029	0
10.8	0.0113	10.56845
19.3	0.0246	18.88621
29.8	0.0414	29.16109
40.4	0.0581	39.53382
50.4	0.0731	49.31942
60.5	0.0906	59.20288
70.4	0.1062	68.89062
79.9	0.1215	78.18694
70.8	0.108	69.28205
60.3	0.0913	59.00717
50.5	0.0766	49.41728
39.8	0.0598	38.94669
30	0.0446	29.3568
20.2	0.0289	19.76691
10	0.0136	9.7856
0	-0.0031	0

Regression Output:	
Constant	2.3348
Std Err of Y Est	0.838696
R Squared	0.998942
No. of Observations	17
Degrees of Freedom	15
X Coefficient(s)	624.8626 kN/Volt
Std Err of Coef.	5.251049

B.2 Range 1VDC-X100

Instron % FS (%)	Impact System (Volts)	Instron Force (kN)
0	-0.0031	0
10	0.0235	9.7856
20	0.054	19.5712
30.1	0.0851	29.45466
39.9	0.1172	39.04454
50.2	0.1485	49.12371
59.9	0.1794	58.61574
70	0.211	68.4992
80.6	0.2421	78.87194
69.4	0.2101	67.91206
60.1	0.1831	58.81146
50.9	0.154	49.8087
40.1	0.1216	39.24026

Regression Output:	
Constant	1.349338
Std Err of Y Est	0.673723
R Squared	0.999311
No. of Observations	17
Degrees of Freedom	15
X Coefficient(s)	318.0095 kN/Volt
Std Err of Coef.	2.155367

30.4	0.0913	29.74822
20.7	0.0616	20.25619
9.8	0.0274	9.589888
0	-0.0031	0

B.3 Range 2.7VDC-X100

Instron % FS (%)	Impact System (Volts)	Instron Force (kN)
0	-0.0031	0
10.2	0.0717	9.981312
19.7	0.1488	19.27763
29.7	0.2331	29.06323
39.9	0.3209	39.04454
60.4	0.4954	59.10502
70.2	0.5792	68.69491
80.1	0.664	78.38266
70	0.5802	68.4992
60.3	0.5012	59.00717
50.5	0.4213	49.41728
40	0.334	39.1424
30.4	0.2538	29.74822
20.8	0.1754	20.35405
10.1	0.0828	9.883456
0	-0.0022	0

Regression Output	
Constant	0.706496
Std Err of Y Est	0.698064
R Squared	0.9993
No. of Observations	16
Degrees of Freedom	14
X Coefficient(s)	117.0178 kN/Volt
Std Err of Coef.	0.82774

B.4 Range 5VDC-X100 :

Instron % FS (%)	Impact System (Volts)	Instron Force (kN)
0	-0.0031	0
5.1	0.0561	4.990656
10.1	0.1358	9.883456
15.4	0.2043	15.06982
19.7	0.2819	19.27763
25.3	0.3621	24.75757
30	0.437	29.3568
34.9	0.5193	34.15174
40	0.5996	39.1424
44.9	0.6749	43.93734
50.3	0.7611	49.22157

Regression Output	
Constant	0.806491
Std Err of Y Est	0.541864
R Squared	0.998775
No. of Observations	20
Degrees of Freedom	18
X Coefficient(s)	63.89549 kN/Volt
Std Err of Coef.	0.527481

45.1	0.6804	44.13306
40.2	0.6052	39.33811
34.7	0.5241	33.95603
30.2	0.4553	29.55251
24.8	0.373	24.26829
19.6	0.295	19.17978
14.6	0.2193	14.28698
9.5	0.14	9.29632
0	-0.002	0

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